

LUX - Linac-based Ultrafast X-ray source

A Recirculating Linac/Laser-based Femtosecond Facility for Ultrafast Science

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1. What will be built? A recirculating linac user facility is proposed to address the growing national and international need for ultrafast x-ray scientific research. The LUX facility is based on existing accelerator technology, coupled with an array of advanced tunable femtosecond lasers, and is capable of performing an enormous variety of pump-probe type experiments with soft and hard x-rays. The facility has been specifically designed with a view toward solving problems in ultrafast science, and its impact will be across all fields of science, from biology, chemistry, and physics, to novel areas such as quantum computing, spintronics, and highly nonlinear phenomena.

The recirculating linac accelerates picosecond-duration electron bunches to 2.5-3 GeV. Intense soft x-rays are produced by high-gain harmonic-generation (HGHG) - a laser-seeded process in a cascaded series of undulators, resulting in enhanced radiation at selected harmonics of the seed. The coherent soft x-rays can be tuned over a range of tens of eV to 1 keV, and ultrashort seed laser pulses produce pulse durations of 50-200 fs. Hard x-rays are produced by spontaneous emission of the electrons in narrow-gap, short-period undulators. By use of a novel bunch tilting process followed by optical compression, hard x-ray pulse durations of 50-100 fs are obtained over a range of 1-10 keV. Synchronization of the x-rays with lasers is critical for experiments, and optical pulses initiate both HGHG seed lasers and experimental end station amplifiers for precise timing. The femtosecond x-rays are produced at a 10 kHz repetition rate, with variable polarization, and with peak fluxes comparable to third generation light sources. With these capabilities, the LUX facility allows unprecedented studies of time domain processes with x-rays.

The facility has capacity for approximately 20 endstation bays, each with integral laser systems for pump-probe experiments, and an initial complement of 8 beamlines is sought. Multiple user groups may set up at a given beamline, running in shifts, and approximately 60 user groups are accommodated round the clock for 2-3 month periods necessary to perform challenging new time-resolved x-ray science experiments in magnetism, spintronics, structural biology, phase transitions, soft condensed matter, and chemical dynamics. The LUX facility has flexibility for upgrades, when experiments require higher fluxes and shorter pulses. An energy recovery option can be introduced for higher powers, and additional tilting, slicing, and electron bunch shaping possibilities offer the potential for high energy 10 fs pulses in the future. With the possibility for amplification of attosecond seed laser pulses, the facility is well positioned to remain the major contributor to ultrafast x-ray dynamics in the world for many years to come.

From the many exemplary studies already presented at workshops, a substantial grass roots effort to begin the field of ultrafast x-ray science has already occurred, and there is no doubt that the LUX facility will be in high demand and oversubscribed. The facility will be unique among DOE ventures, because it marries ultrafast time-domain measurements with x-ray science. The whole spectrum of already-available x-ray determinations, long a staple at synchrotron facilities, and vigorously producing results in all fields of science, would be open to time-dependent measurements. The unique design of the LBNL facility will satisfy an enormous range of pulse properties for each area of specialty. There will be outstanding synergism with other facilities such as the Advanced Light Source (ALS) and the Molecular Foundry. The x-ray pulse slicing beamline currently under development at the ALS, and capabilities in nanoscience at LBNL, will merge directly into the important science accomplished at LUX, and the facility will become an international attraction for time-dependent measurements. The extensive expertise in ultrafast laser measurements and laser development in the San Francisco Bay Area ensures a high likelihood of finding solutions of unique and challenging scientific problems, and an exciting environment for students to flourish in an emerging field. The facility will be as much a laser-related set of tools as an accelerator system, with world-renowned expertise in how to produce and use ultrafast lasers and x-rays to solve real scientific problems. We anticipate that advances in lasers in the next decade will be remarkable, and these advancements will also represent continual upgrades to the facility, both through seeding and for direct excitation at end stations, even without major changes to the accelerator structure.

2. What is the importance of the science? Ultrafast x-rays have been identified world-wide in numerous workshops and reports as a key area ripe for new scientific investigations (see web sites below). Lasers successfully cover most of the visible, infrared, and ultraviolet regions of the spectrum with both high resolution and very short pulses. Thus, experimentalists have utilized lasers to tremendous advantage for thousands of time-dynamics investigations, many absolutely critical to the scientific fields of solid state physics, semiconductors, photochemistry, and photobiology. Until now, ultrafast time domain studies in the x-ray region have been almost completely lacking. By use of synchrotron radiation and by novel conversion of intense laser pulses into soft and hard x-rays, scientists have been able to perform some of the first innovative experiments recently, such as Bragg diffraction studies of phase transitions, time-resolved Laue diffraction of myoglobin-CO reversible binding, femtosecond photoelectron spectroscopy, and even attosecond electron redistribution in Auger electron processes. However, these laser-based x-ray fluxes are low, the signal levels weak, and experiments are challenging to accomplish by individual scientists. The LUX recirculating linac-based facility proposed here provides an increase of x-ray flux by several orders of magnitude, is accessible to a large number of users, with resources available for set-up of pump-probe femtosecond-scale time resolved experiments utilizing ultrafast lasers.

While the approximately 40 available light sources in the world are largely limited to static spectroscopies, microscopies, and structures, this facility will be the first designed from the start as a user facility for femtosecond x-ray dynamics, with precise timing as an integral requirement. The LCLS has the potential to demonstrate some of the first exciting ultrafast x-ray studies with an accelerator-based machine. LUX will be a highly refined ultrafast x-ray source, offering higher repetition rates but lower pulse energies than LCLS, tunability, and

precision timing with other laser sources for excitation and probe experiments. It will accommodate many users at one time across the whole spectrum of experimental possibilities. The science to be carried out with the LUX facility cuts across all scientific disciplines.

By combining both *diffraction* to explore nuclear positions in real time and *spectroscopy* to interrogate electronic and atomic states and their structural parameters and chemical environments, the facility represents a powerful combination to address scientific problems. Broad categories of possible experiments include:

- Photoinduced phase transitions**
- Metal-insulator photo-induced transition**
- Magnetics, photon-excited ferromagnetism, spintronics**
- Time domain structural biology**
- Solute-solvent structural dynamics and charge switching**
- Surface transformations**
- Laser-induced continuum dressing of atoms & molecules**
- Nanoparticle physics**
- Plasma physics**
- Liquid microjet photochemistry studies**
- Interfacial phenomena**
- Soft condensed matter, time-domain microscopy**

And the basic techniques of interrogation involve:

- Pump-probe with visible laser pump light**
- Twin x-ray pulses, one and two color**
- Coherence and multidimensional spectroscopies, four wave mixing, x-ray probe**
- X-ray near edge absorption spectroscopy**
- Photoelectron spectroscopy**
- Photoemission microscopy**
- X-ray magnetic dichroism**
- Time-resolved Laue diffraction**
- Magnetic speckle**
- Scanning transmission microscopy**
- Time domain XPS**

Although pump-probe experiments represent some of the most important techniques, involving a femtosecond laser as a pump and the ultrafast linac-based x-ray source as the probe, the facility will also be designed to accommodate rapidly emerging multidimensional coherent laser spectroscopies (e.g. three-laser pump beams and an x-ray probe), as well as two x-ray wavelengths, for double-resonance x-ray pump and probe spectroscopies. Most of these novel forms of spectroscopies with x-rays have not even been delineated yet. The ability to perform high resolution near edge x-ray spectroscopy, magnetic dichroism, time domain speckle, and time-resolved Laue diffraction are critical. Sample damage is kept to a minimum with lower energies and higher repetition rates, in many cases with complete sample regeneration by translation or flow. A few representative examples of the science topics and their importance are discussed below.

Consider a key topic of phase changes in materials, which occur on ultrafast timescales. An example is the important transformation of VO₂ from the monoclinic (insulator) phase to the rutile (metal) phase, which occurs at 340 K. The multiplicity of possible mechanisms, whether the barrier to the phase change is overcome by the thermal excitation of nuclear motions, or by direct electronic carrier excitations, or whether the phase change is accompanied by a barrier lowering, can be explored. A first femtosecond Bragg diffraction experiment on this material has been performed in a laboratory by laser excitation and time-delayed x-ray probing. In that work ~ 2000 Cu K α photons per pulse were generated by intense heating of a copper wire with a powerful ultrafast laser at 20 Hz repetition rate. The LUX facility will provide 4 orders of magnitude more photons and 3 orders of magnitude more repetition rate. By combining Bragg diffraction experiments with tunable x-ray NEXAFS to locate the oxygen atom environments, transient femtosecond photoemission to determine the Fermi level, and variable wavelength pump lasers to excite both phonons and carriers in the material, a comprehensive picture of the phase transition will be obtained. As with many of the possible experiments to be performed at LUX, the time average flux stability is crucial to detect the small, few percent, changes that occur in pump-probe types of experiments. Flux stabilities of the LUX source will be better than 0.1% on 4-second timescales at 10 kHz repetition rates.

Some biological transformations are inherently slow, while others are impressively fast and selective. To date only a few systems have been explored in great detail on ultrafast timescales with lasers, notably the reversible systems of plant photosynthesis and photoreceptors in vision. Two reversible crystalline systems of myoglobin and the yellow protein have already been the targets of time-resolved Laue diffraction investigations at ESRF and the APS at ANL. Damages to the crystals by the intense laser pulses used to induce transitions present many challenges, and without doubt concurrent work will develop new ways to prepare samples of interest. Nevertheless some impressive and tantalizing results have already been demonstrated. Many other biological systems hold promise for important fundamental discoveries and will become the targets of future investigation. By observing intermediates and their transformations in real time, rather than chemical trapping or thermal trapping, remarkable dynamical events in biological systems will be uncovered. What have also not been explored are rapid irreversible processes that might lead, for example, to cancerous mutations. With the relentless drive to improve health-related knowledge, nonreversible photon or particle damages will undoubtedly become a key direction for future experiments on ultrafast timescales. LUX will become a focal point for these advances. Fluxes in the hard x-ray regime from LUX will be comparable to those of other sources, but concentrated in ultrashort pulses of much lower repetition rate. Femtosecond time dynamics will be immediately possible, instead of 100's of ps or nanoseconds currently available. Chirped pulse techniques offer the potential to squeeze even shorter time processes out of future experiments, by obtaining results via rapidly changing photon energies throughout the already-ultrashort pulse duration.

3. What is the readiness of the concept for construction? Feasibility studies carried out at LBNL show that the proposed facility is feasible and can be built with existing technology, with engineering developments for this particular application. These studies have explored a variety of machine concepts in pursuit of a facility to meet the needs of x-ray studies of

ultrafast dynamic processes, leading to the recirculating linac design for LUX. The major components and systems of LUX are already known accelerator technologies: an rf photo-injector, superconducting linear accelerators, magnetic arcs and straight sections, pulsed extraction magnets, transversely deflecting cavities, high-gain harmonic-generation, narrow-gap short-period undulators, x-ray manipulation in optical beamlines, and a variety of short-pulse laser systems. The machine layout is shown in Figure 1. After acceleration to 2.5-3 GeV, the electron bunches pass through undulators to produce radiation over a range of a few tens of eV to 12 keV. EUV and soft x-rays are generated by a seeded free-electron laser process in a high-gain harmonic-generation scheme (HGHH). Hard x-rays are produced by spontaneous emission of the high energy electrons in short-period undulators.

The physics and engineering design has been developed sufficiently to confirm the feasibility of the project, and to produce a preliminary costs estimate with a strong emphasis on accuracy based on available data from recently completed accelerator facilities and budgetary quotes where available. The feasibility study is contained in a web site referenced below. LUX is based on accelerator technologies that have already been successfully demonstrated on operating machines. We have identified engineering development requirements, and developed risk mitigation plans with an R&D program. Significant R&D has already been invested in the accelerator technologies required, and is ongoing in many areas that may be expected to lead to advances beyond our baseline design parameters, and thus to improved future performance.

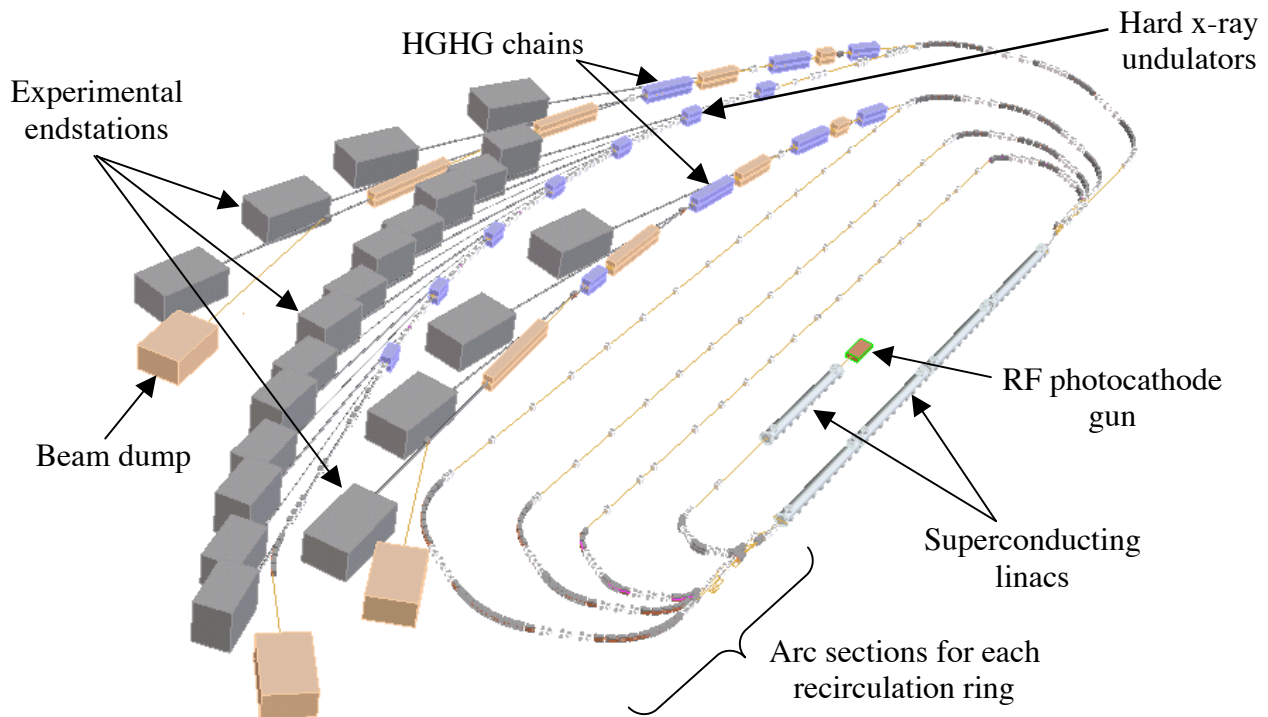


Figure 1. Machine layout showing experimental beamlines HGHH chains, and major accelerator components. The machine footprint is approximately 150x50 m. A capacity of approximately 20 beamlines is shown, an initial complement of 8 is proposed.

Electron pulses are produced at a rate of 10 kHz in high-brightness rf photocathode guns. Two sources are used - one with a conventional circular cross-section beam optimized for production of high-brightness EUV and soft x-ray radiation in the harmonic generation scheme, the other with a flattened cross-section beam for production of hard x-rays. The beam quality requirements of the rf photocathode guns are already demonstrated, with normalized emittance of approximately 3 mm-mrad at 1 nC charge, although higher repetition rates have not been addressed to date. Conventionally, rf photocathode guns employ a simple right-circular geometry or "pillbox" shaped cavities, and operate over 10-100 Hz pulse repetition rate. The cathode is mounted on the cavity axis and electrons are rapidly accelerated by the rf electric fields, minimizing space-charge effects in the low-energy beam. For high duty cycle operation, thermal limitations prevent such designs from operating at an electric field sufficiently high to produce good beam emittance. For the LUX facility we have produced a conceptual design optimized for operation at high gradient and high repetition rate, and producing low-emittance bunches. This design incorporates features that increase cavity surface area to reduce deposited power density, and enhance the accelerating electric field at the cathode. This high-brightness electron source has been carefully designed to minimize the beam emittance, particularly against deleterious effects of space-charge at low energies. We anticipate that a modest R&D program to build a 10 kHz rf gun test facility, and parallel development of photo-cathode materials, will result in successful demonstration of high-reliability, high repetition-rate, low-emittance beams.

Application of a solenoidal magnetic field on the cathode of the flat-beam gun, followed by a specially configured skew-quadrupole channel, allows production of a "flat" beam with large x/y emittance ratio and small vertical normalized emittance, less than 1 mm-mrad. This technique has been successfully demonstrated at Fermilab, with properties within a factor of two of LUX design parameters. We are active partners in the experimental collaboration developing this technique, and we have high confidence in achieving our goals.

The electron bunches from the rf gun are further accelerated in an injector linear accelerator, and the beam is then transported to the entrance of the recirculating linear accelerator. In the recirculating linac the maximum energy of 3 GeV is achieved after four passes through the 750 MeV superconducting rf structure. Identical cryomodules containing multiple accelerating cavities are used for the main linac and the injector linac. The superconducting linacs have advantages in providing a compact and efficient accelerator, extremely stable rf fields, and inherently small perturbative effects on the beam. Incredible advances have been made in superconducting rf technology in recent years, and the parameters of the proven TESLA superconducting rf systems developed at DESY have been used in LUX design studies. Operational high-gradient cw superconducting linacs include the highly successful CEBAF facility at TJNAF, and planned upgrades for that facility also meet the requirements for the linacs for LUX. Our design is for an accelerating gradient of up to 20 MV/m in the main linac, a conservative value given that gradients in excess of 30 MV/m have been demonstrated in some TESLA cavities. The electron bunch repetition interval in LUX is less than the superconducting cavity filling time, and the linacs are more efficiently operated in cw mode. Based on our cryogenic systems models and discussions with DESY and TJNAF staff, we have high confidence that engineering refinements will allow reliable rf systems operation in this mode.

The flexibility of the LUX lattice design allows control and preservation of electron beam transverse and longitudinal emittances, minimizing the influence of collective effects. Longitudinal and transverse dynamics have been modeled from the RF gun through the injector linac and all passes of the main linac. In the injector, a harmonic cavity will be used to control the longitudinal phase-space following the injector linac. The bunch length and magnet bend angle in the lowest energy arcs of the machine result in a regime in which coherent synchrotron radiation emission could be expected, and the vacuum chamber geometry is designed to minimize this effect by shielding against lower-frequency radiation. The recirculating ring arcs are achromatic and isochronous to preserve beam quality. Our studies including particle tracking with cavity wakefields, resistive wall impedance, and magnet errors and misalignments, show only modest emittance growth, with negligible impact on machine performance. The lattice is designed to be flexible and allow manipulation of the bunch phase space on each pass if required, and also to accommodate bunch rates greater than the 10 kHz baseline design.

LUX will have the capacity for energy recovery in the linacs. However, for the baseline beam power of a few tens of kW, the beam will be taken directly to a shielded dump after the x-ray production sections. Energy recovery has been successfully demonstrated at the TJNAF free-electron laser facility, and can be implemented in LUX if beam power demands make the process economical.

At the exit of the final arc the flat-beam electron bunches receive a time-correlated vertical kick in a dipole-mode RF cavity. This imparts to the electron bunch a transverse momentum that is correlated in amplitude to longitudinal position within the bunch. The electrons then radiate x-rays in the downstream chain of undulators and dipole magnets, imprinting this correlation in the geometrical distribution of the x-ray pulse. The correlated x-ray pulse is then compressed by use of asymmetrically cut crystal optics to achieve the ultra-short x-ray pulse length. The bunch deflecting technique is identical to the “crab-cavity” schemes proposed for several electron-positron colliders and has been widely studied. For LUX we have developed a preliminary design for a 7-cell superconducting deflecting cavity. Similar cavities are currently being built at FNAL and initial tests are encouraging.

Narrow-gap in-vacuo superconducting undulator designs provide tunable high-flux sources in the 1–12 keV range. The flux of 10 keV photons from 1 nC bunches at 10 kHz is 6×10^{10} photons/s/0.1%BW for a 4 mm gap, 14 mm period, 2 T peak magnetic field undulator. Similar insertion devices are currently being prototyped and designs are expected to mature in the near future. With developments in rf photocathode technology we envisage improvement in gun performance to operate at higher charge per bunch, giving in excess of 10^7 photons/pulse at 10 keV.

A laser-seeded HGHG cascade produces high-flux, short-pulse photons over an energy range of tens of eV to 1 keV. In this process the circular cross-section high-brightness electron beam is extracted from the recirculating linac, and passed through an undulator where a co-propagating seed laser modulates the charge distribution over a short length of the bunch. This modulation results in enhanced radiation at specific wavelengths and a selected wavelength is amplified in a following undulator, tuned to a higher harmonic of the seed laser. The electron

pulse is then delayed in a short chicane, and the process repeated by modulating a fresh portion of the beam this time with the harmonic radiation produced in the previous undulator. Using a tunable optical parametric amplifier as the seed, and variable undulators, allows significant tunability in four stages of harmonic generation, variable flux up to 10^{13} photons per pulse, and variable pulse duration depending on the seed laser parameters. Two chains of HGHG are proposed, providing exceptional flexibility in producing EUV and soft x-ray pulses. The principle of HGHG has been successfully demonstrated at BNL. Circular polarization is attainable by use of elliptical undulators, and flux stability of 0.1% or better is obtained in seconds from random pulse-pulse flux variations of 10-20% at 10 kHz repetition-rate. The use of tapered undulators allows tailoring of flux to individual experiments, to avoid space-charge effects in, for example, photoemission processes.

Sophisticated laser systems will be an integral part of the LUX facility, providing experimental excitation pulses, stable timing signals, as well as the electron source through the photocathode laser. Each endstation will have its own dedicated laser system and optical manipulation and diagnostics, and optical tables and equipment will be contained within a stable and controlled environment. Multiple tuneable lasers covering a range of 267-3000 nm and pulse durations of ≤ 50 fs are required for experiment initiation, together with temporal and spatial filtering to optimize performance for specific experimental applications. Distribution systems using point-to-point transmission will provide optical seed pulses to each beamline, with feedback based on interferometric measurements to stabilize the path lengths, and matched optics for temporal recompression throughout. Developments in laser technology are expected to result in significant improvements in the coming years, which will be incorporated into our design with minimal impact on accelerator systems.

Synchronization and timing of the ultra-short x-ray pulses to the experimental excitation pulse is critical to studies of ultra-fast dynamics. For LUX we propose to generate inherently stable pulses by using seeded systems and bunch manipulation. In the case of EUV and soft x-ray production, the HGHG seed laser oscillator also drives the sample excitation laser, resulting in timing stability of approximately 20 fs. For our scheme of hard x-ray production by bunch manipulation followed by x-ray pulse compression, we find that the phase jitter of the deflecting cavities with respect to the experimental laser pulse dominates timing issues. Phase and amplitude feedback of the deflecting cavities is expected to provide x-ray pulse to laser pulse timing stability of approximately 50 fs. To stabilize all timing and rf signals in the facility, we propose to use a phase-locked laser oscillator as the facility master oscillator. The RF gun, linacs, and deflecting cavities may thus be phase-locked to the experimental excitation lasers, and timing jitter between the optical laser and the x-ray pulse emitted by the beam minimized. We also propose to develop schemes for using beam-based optical signals to seed the endstation lasers. Optical pulses derived from synchrotron radiation emitted by electron bunches in earlier passes through the accelerator may be used to provide timing reference and laser seed pulses. Each pass through the linac takes approximately 1 μ s, and a timing pulse derived from an earlier pass allows time for manipulation, amplification, and transport of the optical signal directly to the beamline endstations, before the arrival of the x-ray pulse.

Lattice magnets are of conventional water-cooled electromagnet design. LUX vacuum systems are less demanding than typical synchrotron radiation facility storage rings due to the much reduced outgassing from a relatively small average beam current, and the modest lifetime requirements of a pulsed machine. Pulsed magnets to extract the electron beams into the HGHG sections require highly-reproducible fields with rise and fall times of order 10 μ s, readily achievable with solid-state technology and feedback systems.

Conventional facility requirements are similar to those for existing third generation synchrotron light sources, with stable foundations and thermal control of the accelerator enclosures. A two-story building with 91,000 gross square feet of accelerator and experimental facilities at ground level, and 35,000 square feet of laboratory and office space above would provide adequate initial resources, allow for future expansion, and fit within identified sites at LBNL. The facility total power requirement is approximately 8.5 MW.

4. Project management issues. Several sites for the LUX facility have been identified within the LBNL boundary and at nearby locations. A favorable location has been identified adjacent to the ALS, and with room for future expansion. Operating costs are expected to be comparable with existing BES synchrotron-light facilities, although synergies with the existing ALS infrastructure would be a significant advantage and common resources would be used where possible. This would lead to reduced costs in accelerator physics support, technical support staff, repair and maintenance equipment, and administration costs.

Lawrence Berkeley National Laboratory with a Project Team and a Project Director would manage the LUX project. To minimize development costs of technologies not currently core competencies at LBNL, we envisage strong collaborations with other DOE laboratories with special expertise. The R&D program is focused on engineering development and refinement of systems, including a high rep-rate rf photocathode gun, superconducting rf systems, and timing and synchronization systems.

The project is proposed as a three-year capital equipment fabrication project, with one year of conceptual design and two years project engineering design. The funding schedule and associated costs are shown in the table below, with year 1 the beginning of conceptual design studies. Some long-lead purchases are included in year 3, before construction begins.

Based on our in-depth assessment of the LUX facility developed during the feasibility study, we estimate the costs to construct the accelerator and conventional facilities to be approximately \$180M. Additionally, soft x-ray beamlines are approximately \$8M each, and hard x-ray beamlines approximately \$5M each, including undulator, endstation, and laser systems. In addition to these fabrication costs, R&D costs of approximately \$25M are anticipated, plus \$3M in conceptual design studies. Including a conservative 40% contingency on facility costs, the machine and conventional facilities would be a total of \$310M. For a facility with an initial complement of four soft x-ray beamlines and four hard x-ray beamlines, the total cost is then estimated to be \$381M including contingency of 40% on fabrication costs.

The table below summarizes the costs and schedule, in \$FY'03.

Schedule of Project Funding

	Dollars in millions FY'03						□
	Year	Year	Year	Year	Year	Year	Total
	1	2	3	4	5	6	□
Facility cost:	£						£
□ PED	£	15	15				30
□ Construction	£		30	100	60	10	200
□ Contingency	£						93
Other project costs	£						£
□ Conceptual design	3						3
□ R&D	10	10	5				25
□ Pre-ops	£				10	20	30
Total	£	£	£	£	£	£	381

Relevant web sites:

Science Case:

Napa workshop on New Opportunities in
Ultrafast Science using X-rays:
<http://www-esg.lbl.gov/esg/meetings/ultrafast/>

SASE-FEL science case from Bessy in Berlin:
http://www.bessy.de/lab_profile/01.FEL/sc/index.php?language=en

LCLS: The First Experiments:
http://www-ssrl.slac.stanford.edu/LCLS/papers/LCLS_Experiments_2.pdf

Major documentation on LBNL source:

LBNL design feasibility study:
<http://jncorlett.lbl.gov/FsX-raySource/FeasibilityStudy02/>

Related machines and proposals:

SLAC LCLS:
<http://www-ssrl.slac.stanford.edu/lcls/>

Cornell energy recovery linac:
<http://erl.chess.cornell.edu/>

BNL photoinjected energy recovery linac:
<http://nslsweb.nsls.bnl.gov/nsls/org/PERL/>

BESSY FEL:
http://www.bessy.de/lab_profile/01.FEL/index.php?language=en

Daresbury 4GLS:
<http://www.4gls.ac.uk/>

TESLA FEL:
http://tesla.desy.de/new_pages/TDR_CD/PartV/fel.html

TESLA Accelerator:
http://tesla.desy.de/new_pages/TDR_CD/PartII/accel.html

Other related accelerator experiments:

TESLA TTF:
http://tesla.desy.de/new_pages/4000_TTF_project.html

BNL HGHG experiments:
<http://nslsweb.nsls.bnl.gov/nsls/org/AccPhyS/SDL/SDL.htm>

ANL LEUTL:
<http://www.aps.anl.gov/aod/mcrops/leutl/>

TJNAF FEL program:
<http://www.jlab.org/FEL/>

LBNL resources relevant to machine:
Accelerator and Fusion Research Division:
<http://www-afrd.lbl.gov/>